Pre-Exploration Geothermal Resource Assessment for the Raton Basin, Colorado — The Rest of the Story

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Keywords

Geothermal power, Raton Basin, Colorado, sedimentary, permeability, thin sections

ABSTRACT

Last year a preliminary assessment of geothermal power potential in the Raton Basin, Colorado suggested about 6300 MW heat capacity was available in a 2 km^3 reservoir. Now with real data available, the proof of concept is more established, and a much higher capacity is seen. This paper shows the methodology and results of the research using literature, rock, and well data that suggests 2030 MW heat capacity in a very small (0.25 km^3) engineered geothermal system. However, given the underpressured nature of the basin, including the formation of interest, a well-researched engineering plan, including further geophysical studies, is required to develop an economical, optimal engineered geothermal system.

Introduction

Colorado has excellent potential for geothermal electric power generation. A producing geothermal reservoir requires sufficient volume, heat, permeability, and cap rocks, all of which can be determined from exploration. Geological complexities, rugged terrains, and local resistance to development have hampered exploration efforts to determine if these requirements are present. Coal bed methane (CBM) production in the Colorado portion of the Raton Basin results in large quantities of co-produced hot water, suggesting heat requirements may be met in the basin. Research for geothermal potential commenced on a study area in Las Animas County bounded on the west by the Culebra Range and on the east by the city of Trinidad (Figure 1).

General Data Collection

Initial research entailed collecting and examining data for the study area. A wealth of geological research, with minimal geophysical research performed, has been published but most information refers only to the shallower subsurface relative to coal mining and subsequent CBM production. After reviewing the area stratigraphy, the Sangre de Cristo Formation of late Pennsylvanian to mid-Permian age was chosen as a potential reservoir target. The formation consists of compressed sandstones with shale and limestone stratifications (Lindsay and Schaefer, 1984). Its depth and thickness may provide the volume and heat requirements for geothermal power production. Figure 2 shows the relative location of the Sangre de Cristo Formation in the Colorado portion of the Raton Basin.

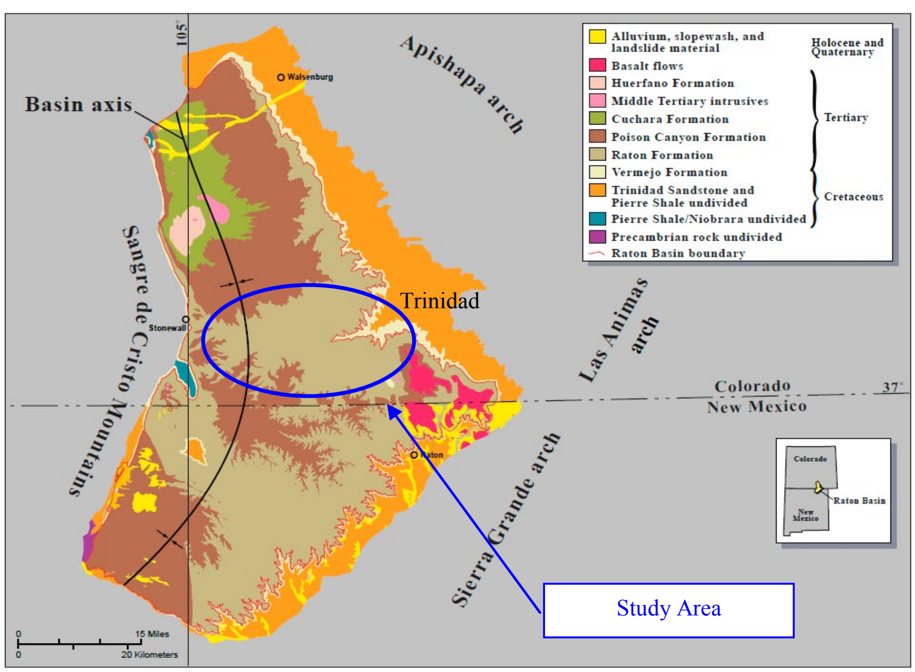

Figure 1. Schematic of the Raton Basin and its geological boundaries (modified from Johnson and Finn, 2001).

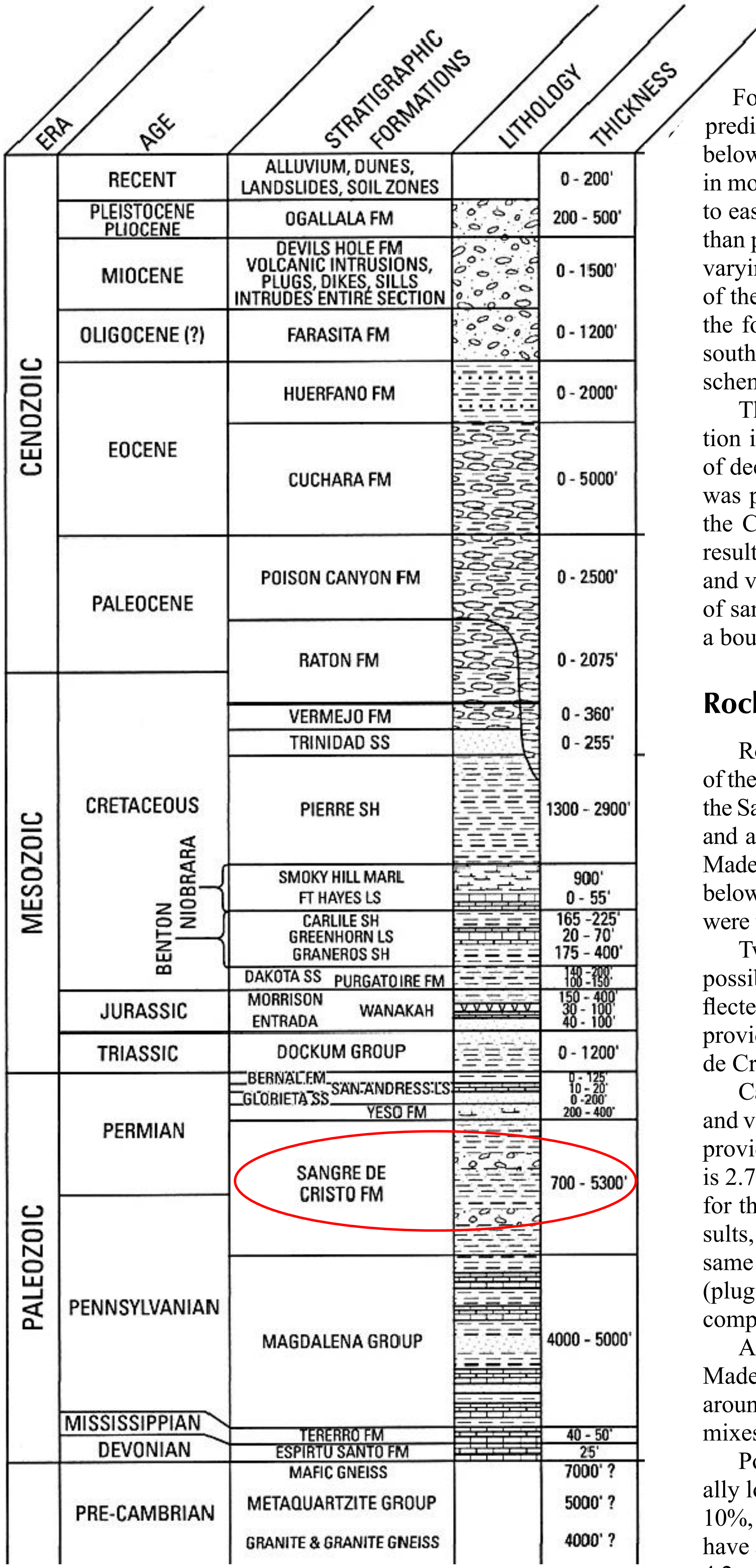

Figure 2. A general column showing Raton Basin stratigraphy based on well data and outcrop correlations (modified from Johnson and Finn, 2001). The Sangre de Cristo Formation is highlighted by the red circle.

Historical papers compared the subsurface of the Raton Basin to the more-studied Denver Basin, with the Sangre de Cristo Formation compared to the Fountain Formation. With very limited well data available, Balz (1965) predicted the Sangre de Cristo Formation to be around 1.5 km below the surface in the study area. Correlating formations posted in more recent well data from townships at similar latitudes west to east show the Raton Basin subsurface is much more complex than previously postulated. The Sangre de Cristo Formation is at varying depths in the study area, with well logs showing the top of the formation at depths just under 2 km (1.8 km). In general, the formation appears to be at shallower drilling depths in the southern areas of Colorado's Raton Basin. Figure 3 provides a schematic of two cross-sections reflecting these complexities.

The exact depth and properties of the Sangre de Cristo Formation is uncertain throughout most of the basin due to a paucity of deep well data. However, a geological study of the formation was performed in an area northwest of the Raton Basin within the Culebra range (Lindsay and Schaefer, 1984). The detailed results describe a complex suite of sediments with many lateral and vertical variations within the formation. The multiple layers of sandstones and shales may provide caprock seals required of a bounded reservoir.

Rock Data

Rock samples were gathered from outcrops within and northwest of the study area (Figure 4). The majority of the samples were from the Sangre de Cristo Formation, some from the Madera Formation, and a few supplied Precambrian Tertiary granitic intrusions. The Madera Formation is part of the Magdalena Group, shown directly below the Sangre de Cristo Formation in Figure 2. These samples were taken for comparisons to the Sangre de Cristo Formation.

Two 1" cylindrical plugs were made from each sample where possible. The Sangre de Cristo Formation heterogeneity is reflected in differing properties between the rock samples. Figure 4 provides a photo of four visually very different plugs from Sangre de Cristo Formation rock samples.

Caliper measurements were made to obtain physical properties, and vacuum-dry and saturation measurements were performed to provide densities and porosities. The average density of the plugs is 2.70 g/cm^3 for the Sangre de Cristo Formation and 2.71 g/cm^3 for the Madera. For densities, and for all further calculation results, large differences are sometimes seen in two plugs from the same rock sample. This can be attributed to perhaps weathering (plugs from exposed side and buried side of sample) or impure components incurred during depositional settling.

Acid tests were performed, and both the Sangre de Cristo and Madera Formation plugs show reactivity in at least one spot on around 25% of the plugs tested. This further alludes to the mineral mixes within the formations, such as limestone.

Porosities of the Sangre de Cristo Formation plugs are generally low, *e.g.* percentages of $1 < \varphi < 13$, with the majority below 10%, resulting in an average of 6.2%. The Madera Formation rocks have a smaller and yet lower range, *e.g.* percentages of $0.9 < \varphi < 4.2$, with an average of only 2.5% porosity. This was expected due to a shorter depositional period at greater depths then the more recent Sangre de Cristo Formation.

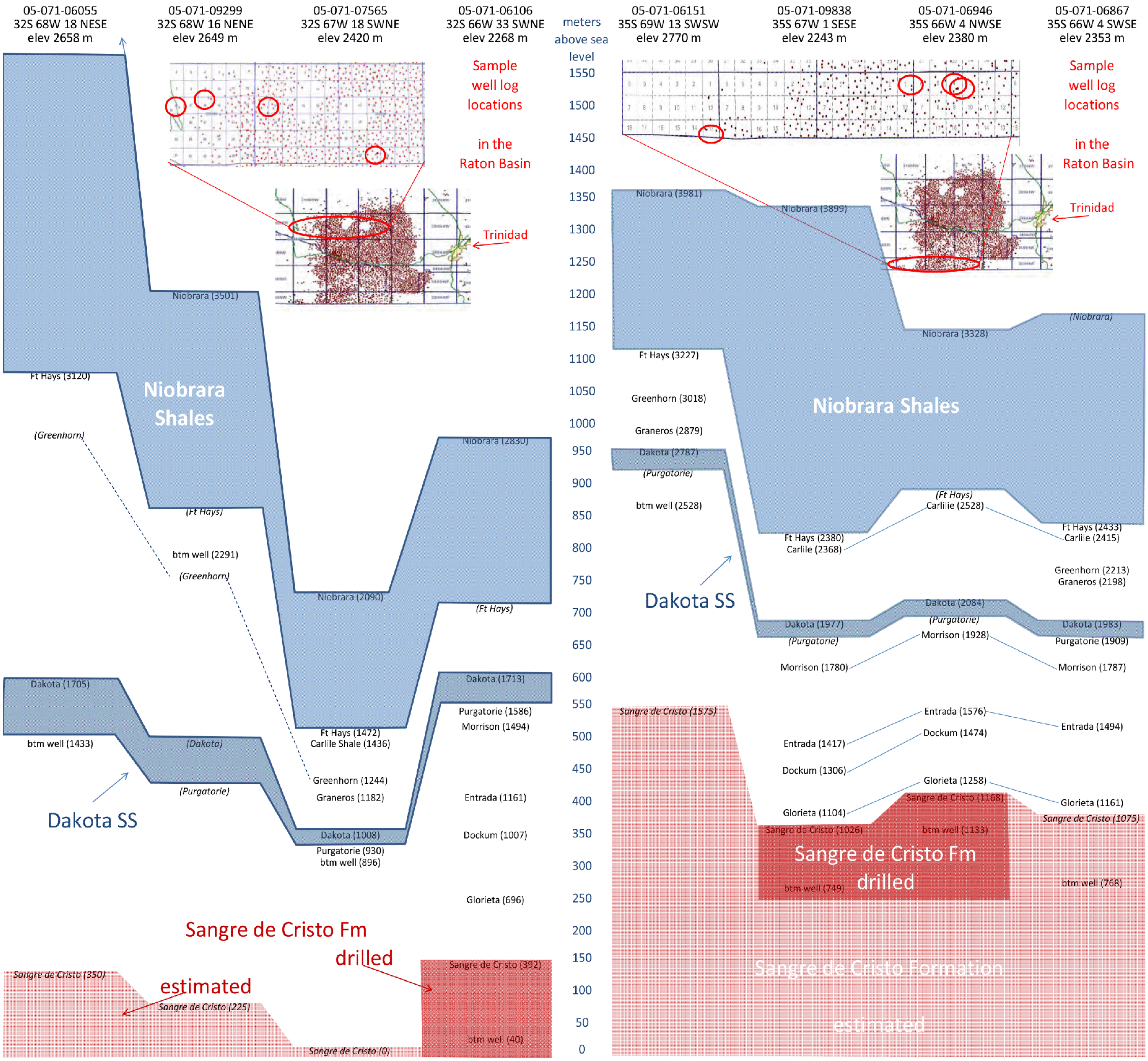

Figure 3. Example formation correlations at similar latitudes, scaled to depths above mean sea level. While the surface altitudes are similar north-to-south in the basin, the Sangre de Cristo Formation appears to be at shallower depths in the southernmost area of the state.

To understand the potential for fluid movement in the Sangre de Cristo Formation, permeability data is also needed. A Hassler Cell and steady-state nitrogen gas permeameter were used to measure gas permeabilities. Due to low porosities and limited maximum input pressures (85 psi) available, the standard operating procedure of varying the flow rates gave erratic data. Instead, a method was devised where the pressure regulator was adjusted to provide four different input pressures to work with; this gave more reliable results. Fluid permeabilities were then found using the Klinkenberg effect y-intercept on graphs of gas permeability *vs* inverse mean pressures (see Figure 5).

Permeabilities are generally related to porosity, *i.e.* lower porosities yield lower permeabilities. As suspected, two of the most porous Sangre de Cristo plugs yield barely over 1.07 millidarcy (md), with the majority at less than 100 microdarcys (µd). The Madera plugs all have permeabilities of less than 40 µd with an average of only 19 µd. One Precambrian granitic intrusion plug was run (most granitic samples were too friable to produce usable plugs). This plug has a porosity of 1.6%, and a permeability of only 1.5 µd.

Thermal conductivity (TC) measurements on the samples were provided by the Colorado Geological Survey (CGS). While TC alone cannot determine the rate of heating in a rock (other variables are required such as heat capacity of the rock flow of fluid, grain shape, *etc.*), TC can help characterize the rate of change of the temperature (Rzhevsky and Novik, 1971). In general rocks are poor heat conductors, with a common TC average of sandstones given as 2.5 mW/m°C (Morgan, 2009). The range of TC on the Sangre de Cristo plugs runs from 1-4 mW/m°C, with their average at 2.3 mW/m°C. The Madera plugs have a 1.7 mW/m°C average.

Six thin sections were prepared, four from the Sangre de Cristo Formation and two from the Madera Formation. Some general observations were provided by the Colorado Geological Survey:

- The low porosity of both formations is confirmed.
- The samples represent incomplete weathering and immature sediments, i.e. fine-grained but angular to sub-rounded
- The samples range from mostly quartz to less than 20% quartz, most being fine-grained arkose (high feldspar content)
- Very low clay content is visible, indicating competent rocks that will perform well with hydraulic fracturing

Figure 6 is a photo of the sections prepared. The top four are the Sangre de Cristo samples, the bottom two are the Madera samples. Note again the differences in textures and colors.

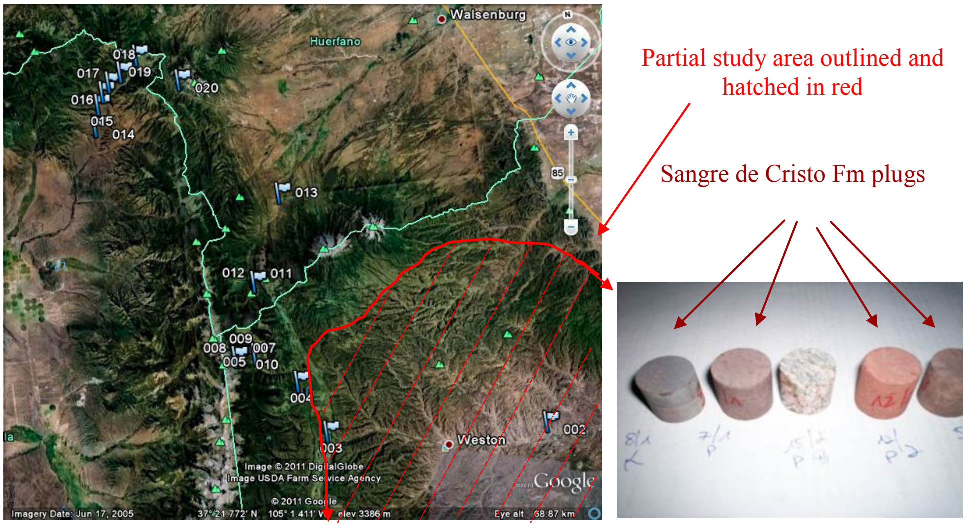

Figure 4. Rock sample locations marked by flags in map on the left. The photo on the right shows four Sangre de Cristo Formation plugs (the middle one is a granitic intrusion) and demonstrates the diverse lithology of the formation.

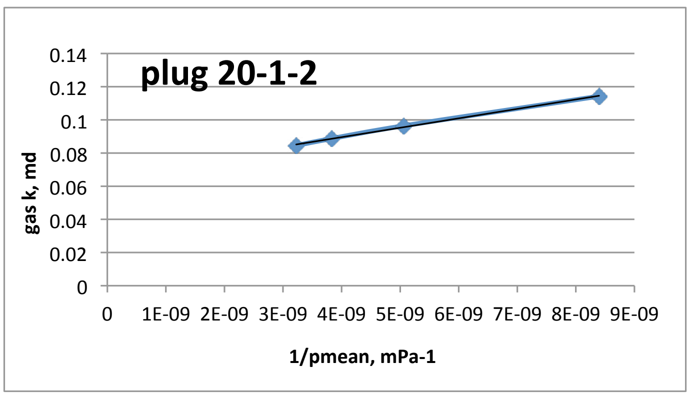

Figure 5. This Sangre de Cristo Formation plug has a fluid permeability of 0.067 millidarcy, or 67 microdarcys, reflected by the y-intercept of the interpolated line.

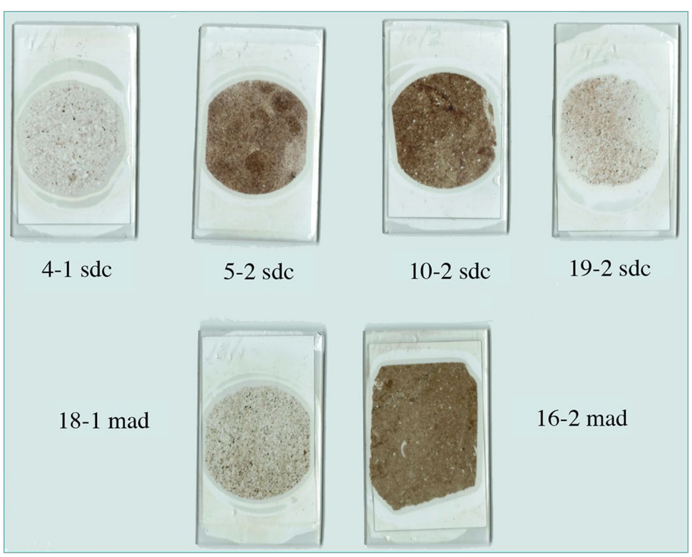

Figure 6. Thin sections prepared from rock samples gathered. The top four are samples from the Sangre de Cristo Formation, the bottom two are from the Madera Formation. Both formations show a variety of physical properties.

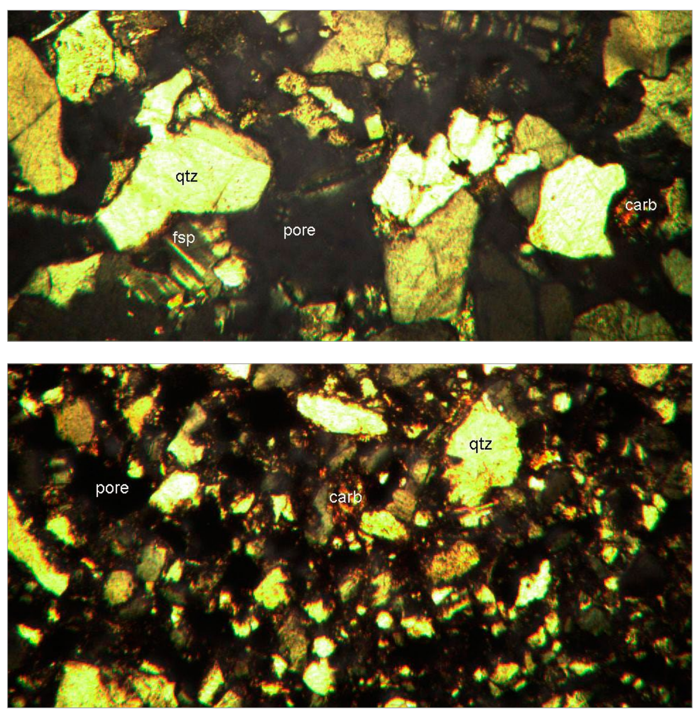

Figure 7. Two 1 mm portions of the thin sections are imaged here. The top image represents Sample 4-1 in the previous figure, with porosity of 12.9% and permeability of 1.07 millidarcy. The lower image is Sample 5-2, with 6.0% porosity and only 46 microdarcys.

Figure 7 shows the microscopic images of two slides from the Sangre de Cristo Formation; referring to Figure 6, these are 4-1 and 5-2. The images represent approximately 1 mm of the slide. The top slide, from Sample 4-1, represents the most porous rock sample gathered, with 12.9% porosity and 1.07 millidarcy permeability measured. The bottom slide of Sample 5-2 is representative of the average porosity of 6.0% and only 46 microdarcys permeability.

Naturally-occurring radioactive decay can be a contributor to high heat flows and a hot dry rock heating source. At the Soultz-sous-Forêts geothermal power plant in France, some radioactivity was measured (far below any danger levels) when a subsurface pump was removed for repair (Albert Genter, personal communication). The Raton Basin was once mined for uranium, and its high heat flows are not fully understood. Therefore, the rock samples were run through a scintillator to compare their radioactivity to the potassium chloride (KCl) calibration sample. While one Sangre de Cristo rock recorded 16% more radiation than the KCl sample, most have less than 25% the amount of radiation of KCl, averaging 17% for the Sangre de Cristo, and 11% for the Madera rocks. As such, the samples collected can be deemed non-radioactive.

Well Data

Some well data were provided by the CBM operator but most were obtained from the Colorado Oil and Gas Conservation Commission (COGCC) website. Bottom-hole temperatures (BHTs) were extracted where possible. From these data, linear thermal gradients were extrapolated to 1.5 km depth and deeper. No temperature corrections were applied, as multiple entries for wells in both sources showed varying BHTs.

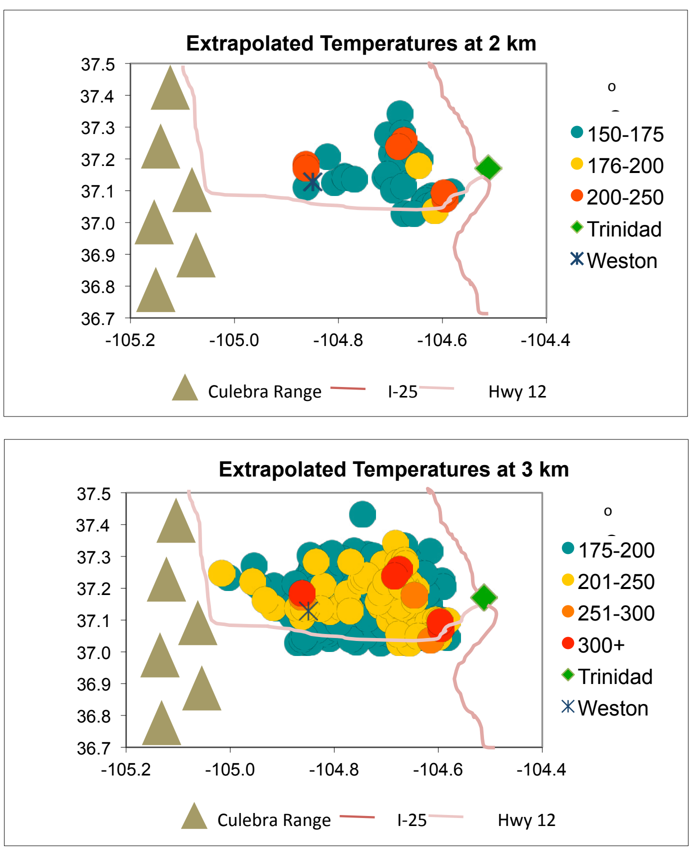

Figure 8. Temperatures at depth based on linear thermal gradients calculated from posted BHTs in the Raton Basin study area.

At 2 km depth, temperature extrapolations show six wells over 200°C and over 800 wells from 100°C and 200°C. At 3 km depth, five wells show over 300°C potential, with over 80 showing from 200°C and 300°C temperatures. There are high BHTs found throughout the basin. Five of the eight deepest wells from all operators and owners shown in Figure 3 have BHTs over 100°C at around 2 km depth. Figure 8 gives a sample distribution of extrapolated temperatures within the basin.

Initially, basin heat flows were calculated using a generic 2.5 mW/m°C thermal conductivity, as no specific TC data were available. While some actual TCs are now known for the lower formations, none are for the formations above the target reservoir depth, so the heat flows will remain calculated using the generic TC. This has resulted in an average heat flow of 128 mW/m^2 found from the data in the study area. This is almost double the global continental average of 65 mW/m^2, with only 13 of over 1100 wells showing less than average values. Only seven wells in this dataset are over 2 km deep, so the Raton Basin average heat flow could increase if more deep well data were available.

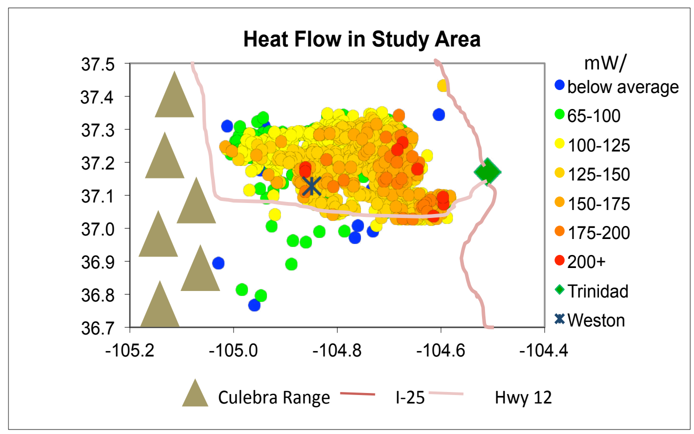

Figure 9. Study area heat flow distribution.

Figure 9 shows how the calculated heat flow is distributed throughout the study area. As can be seen, higher heat flows in general are seen in the easternmost section of the study area. This could possibly be attributed to groundwater flowing west to east, allowing more residence time in the hot depths. This suggestion may also explain the hotter temperatures seen in the east in Figure 8. Higher known BHTs due to heat conduction from depth allow for higher extrapolated temperatures.

Geothermal Power Potential

Using rock properties and temperature data, an estimate of the stored anomalous heat in a defined reservoir was calculated. No calculations were made for the fluid content, as they generally only contribute a small amount compared to the rock. Sangre de Cristo Formation plug data is provided for the rock property variables. Equations 1 and 2 provide a simple formula for calculating stored heat. Equation 1 calculates the amount of anomalous heat stored in a rock, and Equation 2 provides the heat stored in a reservoir.

$$\Delta Q_R = (1-\Phi)\,\rho_P\,C_R\,[T_z - T_{z0}] \qquad \text{[Eq 1]}$$

$$Q_R = \Delta Q_R\,(V) \qquad \text{[Eq 2]}$$

Parameter	Variable	Value
anomalous heat stored in rock at a location:	ΔQ_R	calculated J/m^3
avg porosity:	Φ	0.062
avg grain density:	ρ_P	2.7 g/cm^3
specific heat sandstone:	C_R	0.92 kJ/kgK
temperature at depth (2.5 km), choose :	T_z	200°C
ambient gradient temperature at 2.5 km:	T_{z0}	90°C
heat stored in an area of stated volume:	Q_R	calculated J
propose pilot reservoir of 1 km long x 0.5 km wide x 0.5 km deep:	V	0.25 km^3

Result:

$Q_R = 6.41 \times 10^{16}$ J = 1.78×10^{7} MWh

= **2030 MW gross power production capacity**

Many factors go into determining the net power production: fractures in place, water flow, plant equipment efficiency, and others. Grant and Garg (2012) give good examples of the difficulty in predicting heat recovery factor. At the surface, temperature and water flow can impact the equipment efficiency; generally the higher of both the more efficient the equipment. A conservative heat recovery factor of 2% was presented in a discussion of a study in Virginia (Blackwell *et al*, 2010). If this factor were used for preliminary calculations in the Raton Basin, a very small geothermal reservoir could provide over 40 MW of power.

Engineered Geothermal System

While this study cannot begin to offer guidance on designing the reservoir, a critical point about the Raton Basin that will affect the design of the reservoir still needs to be discussed. Nelson *et al* (2012) showed that the Raton Basin is underpressured even at the depths of the Sangre de Cristo Formation. The exact reason is not understood. There is limited recharge on the western flanks of the basin through faulting and formation exposure, yet there is no outcropping of the formation on the east flank. However, much of Colorado has underpressured zones from similar deposition and uplifting geological activity. This environment must be considered while designing a pilot plant, and could actually be of economic benefit, requiring less surface pressures during hydraulic fracturing.

Drilling in the hotter depths of the Raton Basin could also take advantage of the temperature difference effects on the sandstones. Using a fluid modulus of 2 GPa, a quartz grain bulk modulus of 36.6 GPa (Dvorkin and Gutierrez, 2001), and the Voigt-Reuss-Hill equation, the bulk modulus of the Sangre de Cristo will be around 17 GPa. Pure sandstone offers a higher result. Jaeger *et al* (2007) offer a simple equation to suggest induced thermal stress. Providing a temperature difference of only 50°C while injecting water in the formation will provide about 2.5×10^7 MPa stress on contact.

The above illustrates how much detail must be considered by the reservoir engineer. In addition, high water flows through the reservoir can exacerbate temperature drawdowns, limiting the lifespan of the reservoir. This is why often multiple injection wells are utilized by a single extraction well. A pilot plant location must take this into account. Figures 8 and 9 show a potential location near the town of Weston. Will existing infrastructure at this location be able to support multiple wells, or should a more eastern location be considered due to the higher temperatures at shallower depths found there? The primary operator of the basin must be consulted, especially if the Weston area location is selected for further study. Heat transfer is also affected by fluid flow direction. Will the stratification in the Sangre de Cristo Formation help or hinder the reservoir heat maintenance? Hydrogeologists may also need to be consulted for their expertise in fluid flows.

Power Plant Economics

The Colorado portion of the Raton Basin shows definitive geothermal power production potential. Due to low permeabilities and existing water in the Sangre de Cristo Formation, fracturing and injection would be required even for a small EGS power plant. Economic analysis must be performed to determine if a modular, binary plant would be a cost-effective option. Binary plants can provide power with water temperatures from 90°C to 150°C, as they use the geothermal water to heat a low flash-point working fluid to spin the turbines. However, if temperatures at depth exceed 150°C, a more efficient flash steam plant should be considered. Yet another option for better efficiency would be installing a dual binary system power plant.

Site logistics also influence the economics of a potential power generating station. Can an existing condenser be used? Can existing wells be repurposed for geothermal production or injection wells? Are power lines available and able to increase their load? Will the operator utilize all electricity produced replacing its natural-gas powered wells? Here again, a development project would require the involvement of the primary CBM operator, as well as the local utility providers. If the pilot plant is located near the Trinidad, can cascading operations be developed, providing heat and/or warm water to a spa, greenhouses, and/or city buildings prior to reinjection? This option would entail the City of Trinidad's cooperation – both its government and its citizens. A good marketing program could result in local citizens taking 'ownership' and pride in the project. This, and added jobs and amenities for the city could go far to prevent the not-in-my-backyard attitude that often precludes new developments.

Recommendations and Conclusion

EGS reservoirs have a minimum of two wells – one for extracting hot fluids and one for reinjecting cooled fluids. Fluid movement from the injection well to the production well must be slow enough to allow reheating prior to extraction. The fluids must also be extracted at high enough volumes to efficiently supply the surface equipment. Many variables are involved in designing a successful geothermal reservoir system.

More detailed work with existing well logs should be performed to provide a better understanding of the subsurface, and to further pinpoint an area for a pilot geothermal program. Further geophysical work can also be performed to assist in identifying a plant location. If a pilot plant is developed in the Weston area, the experience can be utilized to design another power plant near Trinidad, where yet more potential appears in Figures 8 and 9.

Developing a Raton Basin geothermal power plant has several benefits. The Raton can become a “research lab” for geothermal exploration and EGS development in a sedimentary basin. The economics (compared to granitic basements), technology, and onsite expertise available together make this a very feasible venture. The Raton Basin could provide the first geothermal power plant in Colorado.

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